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PII: S0016-2361(97)00004-5

Fuel Vol. 76, No. 8, pp. 771–775, 1997
Published by Elsevier Science Ltd
Printed in Great Britain
0016-2361/97 $17.00+0.00

Growth of forages on acid soil amended with flue gas desulfurization by-products

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(Received 19 January 1996)

To assess beneficial or detrimental plant growth effects when flue gas desulfurization by-products (FGD-BPs) are applied to acid soil, experiments were conducted in a greenhouse to determine growth of forages (orchardgrass, tall fescue, switchgrass, eastern gamagrass, white clover and alfalfa) on an acid pH 4.6 soil with different levels of three FGD-BPs and chemical-grade calcium carbonate (limestone), calcium sulfate and calcium sulfite. The FGD-BPs tested were high-$CaSO_4$, high-$CaSO_4$ enriched with Mg, and high-$CaSO_3$. Maximum total plant dry matter (DM) was obtained when ~25% of high-$CaSO_4$ FGD-BP or ~2.5% of high-$CaSO_4$ FGD-BP + Mg was incorporated into soil mixes; DM decreased at higher levels of addition. High-$CaSO_3$ FGD-BP benefited growth of all species when added at levels up to ~3.0% in soil mixes. Beneficial plant responses were higher for the high-$CaSO_4$ FGD-BPs than for the high-$CaSO_3$ FGD-BP. Maximum beneficial plant responses for limestone were at ~0.25–0.50% and for $CaSO_4$ at 50–75% in soil mixes, which were comparable with the high-$CaSO_4$ FGD-BP and high-$CaSO_4$ FGD-BP + Mg responses. Chemical-grade $CaSO_3$ gave no beneficial growth effects on any of the plant species. The FGD-BPs used in this study benefited forage growth when added at appropriate levels. *Published by Elsevier Science Ltd.*

(Keywords: FGD by-products; soil amendment; plant growth)

Large amounts and several types of coal combustion by-products (CCBs) are obtained when power plants burn coal to generate electricity. To meet standards of the US Clean Air Act, particulate and chemical substances must be removed from emissions before gases can be released to the atmosphere. One major chemical substance produced, especially when high-sulfur coal is burnt, is sulfur dioxide (SO_2). Wet scrubber technology currently used removes much of the SO_2 to form large amounts of flue gas desulfurization by-products (FGD-BPs).

A survey on the production and use of CCBs in the USA[1] reported that ~80.3 million tonnes (88.5 million short tons) of CCBs were produced in 1993. The CCBs produced consisted of 54% fly ash, 23% FGD BPs, 16% bottom ash and 7% boiler slag. By the year 2000, it has been estimated that 40% of the CCBs produced (45 million out of 113 million tonnes) will be FGD-BPs[2]. While ~22% of the CCBs produced in 1993 was used beneficially (22% of fly ash, 30% of bottom ash and 55% of boiler slag), only 6% of the FGD-BPs was so used, Additional beneficial uses of FGD-BPs are needed. Although both fluidized bed combustion (FBC) and FGD BPs have been described as FGD-BPs elsewhere, the present authors consider FBC-BPs to be different and they are not included in this discussion.

A beneficial use of FGD-BPs could be as an amendment or potential liming agent on acid soils and/or sites (e.g. acid mine spoils). The use of some FGD-BPs as liming agents on acid soils appears attractive when the process used in their formation results in products containing considerable lime or lime-quality substances. However, many FGD-BPs do not contain these lime substances and are relatively high-grade $CaSO_3$ or $CaSO_4$ (gypsum) products. Present clean coal technologies produce FGD-BPs with both high $CaSO_3$ and $CaSO_4$, depending on the amount of oxidation of the by-product during production and/or the extent of air (O_2) exposure during storage and handling.

Gypsum ($CaSO_4 \cdot 2H_2O$) is readily soluble and may leach through soil to mitigate the toxicity of aluminium (Al) and other elements in acid (pH < 5.0–5.5) soils, especially subsoils. Improved soil physical properties may also occur with enriched Ca and S. Both Ca and S are nutrients required for plant growth in relatively high amounts. Plant roots usually grow more readily in $CaSO_4$-amended subsoils because of improved soil properties. The improved root growth makes additional water and nutrients available to plants. Roots at greater soil depths may also enable plants to survive droughts better by obtaining moisture from lower soil profiles during periods of limited rainfall. Such effects have been noted for maize (*Zea mays* L.) grown on an oxisol amended with gypsum[3]. In addition to Ca and S, many other mineral nutrients required for plant growth may be present in FGD-BPs. On the other hand, levels of B and some heavy metals may be sufficiently high in FGD-BPs to be toxic to some plants.

The beneficial effects of gypsum on the growth of many crop plants have been reviewed[4,5]. Even though gypsum benefits plant growth in many cases, detrimental effects, especially to root growth, have also been reported[6,7]. For example, maize grown under greenhouse conditions on acid soil (pH 3.9) showed reduced growth, especially of roots, when $< 100\ g\ kg^{-1}$ of high-$CaSO_4$ FGD-BPs or chemical-grade $CaSO_4$ was used, which was overcome when the level of BP or $CaSO_4$ was $\geq 250\ g\ kg^{-1}$ (up to $750\ g\ kg^{-1}$). Growth of these plants was depressed below that on unamended soils probably because Ca displaced Al from soil exchange sites into the soil solution, resulting in Al toxicity. Maize grown on this same acid soil mixed with up to $10–20\ g\ kg^{-1}$ of several high-$CaSO_3$ FGD-BPs received some benefit, but growth decreased dramatically when higher levels of these FGD-BPs were added. On the same soil amended with chemical-grade $CaSO_3$, maize growth was lower than on unamended soil at levels as low as $2.5\ g\ kg^{-1}$ soil, and became progressively lower as $CaSO_3$ increased. Growth of weeping lovegrass [*Eragrostis curvula* (Schrader) Nees] and lespedeza [*Lespedeza cuneata* (Dum.-Cours.) G. Don] was depressed when cultivated on 100% FGD-BP without leaching or without added N, P and K[8]. In field studies, alfalfa (*Medicago sativa* L.) growth was enhanced over controls when gypsum was surface-applied to acid soil[9].

The objective of the present study were to determine effects of different rates of application of three FGD-BPs (representing BPs produced by coal-burning power plants) and chemical-grade $CaCO_3$, $CaSO_4$ and $CaSO_3$ on dry matter of six forage species.

EXPERIMENTAL

Experiments were conducted in a greenhouse using natural and artificial light to extend short days to 14 h length and to provide extra light during cloudy days (400–500 $\mu mol\ m^{-2} s^{-1}$ at plant height). Artificial light was provided by high-pressure sodium lamps.

Plants were grown on unamended and amended acid Lily soil (fine loamy, siliceous, mesic, Typic Hapludult) which had been fertilized with $50\ mg\ kg^{-1}$ N and $143\ mg\ kg^{-1}$ P as NH_4NO_3 and KH_2PO_4. Soil was amended with three FGD-BPs (high-$CaSO_4$ FGD-BP, high-$CaSO_4$ FGD-BP+Mg and high-$CaSO_3$ FGD-BP) and chemical-grade calcium carbonate (limestone), $CaSO_3$ and $CaSO_4$ at different levels (see abscissa of each Figure for the levels used). Some properties of the original acid Lily soil were: 63% sand, 31% silt, 7% clay, 4.49% organic matter; pH 4.82 (1:1 soil:water) and 4.57 (1:1 soil:0.01M $CaCl_2$); 3.02 $cmol_c\ kg^{-1}$ exchangeable acidity and 2.55 $cmol_c\ kg^{-1}$ Al (1M KCl-extractable); 4.00, 55.9, 57.3, 9.8, 89.9 and 66.9 $g\ kg^{-1}$ P (Bray-1-extractable), Ca, K, Mg, Na and S (1M ammonium acetate-extractable) respectively (65% Al saturation); and 60.2, 33.5, 2.81 and 0.11 $mg\ kg^{-1}$ Mn, Fe, Zn and Cu (0.005M DTPA-extractable) respectively. Elements in the extracted solutions were determined by inductively coupled plasma atomic emission spectrometry, except P, which was determined colorimetrically (as vanadomolybdophosphate).

Plant species grown were two cool-season grasses [orchardgrass (*Dactylis glomerata* L., 'Wana') and tall fescue (*Festuca arundinacea* Schreber, KY31)], two warm-season grasses [switchgrass (*Panicum virgatum* L., 'Cave-in-Rock') and eastern gamagrass (*Tripsacum dactyloides* (L.) L., WW1459)], and two legumes [alfalfa (*Medicago sativa* L., 'Vernal') and white clover (*Trifolium repens* L., 'Huia')]. Each plant species was grown at different times, but all FGD-BPs and chemical compounds were included in the same experiment. Length of the growth period was 55, 54, 69, 71, 82 and 59 days for orchardgrass, tall fescue, switchgrass, eastern gamagrass, alfalfa and white clover respectively.

The FGD-BPs and chemical compounds were thoroughly incorporated into the soil by hand. The soil–FGD-BP/chemical compound mixes were moistened with distilled water to near field capacity, enclosed in plastic bags, and equilibrated 7 days at atmospheric temperature before being placed in pots (1.0 kg soil mix per pot) for plant growth. Some chemical properties of the FGD-BPs used are listed in *Table 1*, with additional information provided in Clark *et al.*[6].

Seeds of each plant species were surface-sterilized with 0.1-strength household bleach (NaOCl) for 5 min and rinsed thoroughly with distilled water. Six to eight seeds were planted in each pot. Plants were thinned to three per pot a few days after emergence. Distilled water was added every other day initially and then daily after plants became established, to provide sufficient water for growth. Water was added manually to prevent leaching.

Shoots were severed above the soil surface or crown to terminate experiments, roots were thoroughly washed to remove soil, and crowns were removed from roots. Shoots, roots and crowns were dried separately at 60°C, samples were weighed, and crown mass was added to shoot mass. The design for each experiment was completely randomized blocks with four replications. Means with standard errors of whole-plant dry matter (DM) were plotted as bar charts.

Table 1 Some properties of flue gas desulfurization by-products

	High-$CaSO_4$ FGD-BP	High-$CaSO_4$ FGD-BP+Mg	High-$CaSO_3$ FGD-BP
pH[a]	8.91	9.53	8.68
EC[a,b] ($dS\ m^{-1}$)	1.67	3.35	5.58
CCE[c] (%)	5.0	13.1	69.3
Chemical composition			
S-SO_4 ($g\ kg^{-1}$)	216	176	200
S-SO_3 ($g\ kg^{-1}$)	0.8	1.0	25.9
Ca ($g\ kg^{-1}$)	238	209	178
Mg ($g\ kg^{-1}$)	0.23	22.7	11.8
K ($mg\ kg^{-1}$)	32	165	714
P ($mg\ kg^{-1}$)	60.7	< 0.03	8.8
B ($mg\ kg^{-1}$)	< 0.02	< 0.02	88.4

[a] In 1:1 mixture with water
[b] EC = electrical conductivity
[c] CCE = calcium carbonate equivalence

RESULTS AND DISCUSSION

Without amendment to the acid soil, switchgrass and eastern gamagrass grew the best, orchardgrass and white clover grew fairly well, and tall fescue and alfalfa did not grow well (*Figures 1–4*). Each species responded positively to added limestone, with 0.25 to 0.5% providing highest DM for the plant species tested. Other studies in the laboratory indicated that limestone > 1% provided little or no benefit to plants grown on this soil.

The level of the high-$CaSO_4$ FGD-BP for the highest plant DM of these plant species, except eastern gamagrass (see *Figure 3*), was 10–25% in soil mixes; levels higher than this were detrimental (*Figures 1–4*). Detrimental effects were especially noted for the grasses, while the legumes grew well with 50 and 75% high-$CaSO_4$ FGD-BP. Even at these high levels of this FGD-BP, growth of grasses was not completely inhibited. In other studies, maize grew relatively well at high levels with similar types of BP[6], but levels < 5% in soil mixes were detrimental[7]. Because of the results noted for maize[6,7], the level of high-$CaSO_4$ FGD-BP used in the current study were > 5% for the grasses and legumes.

Orchardgrass, switchgrass and eastern gamagrass had the highest DM with high-$CaSO_4$ FGD-BP + Mg at 1–2.5% in soil mixes, white clover and alfalfa had the highest DM at 2.5–5%, and tall fescue had the highest DM at ~10% (*Figures 1–4*). Although each species benefited markedly

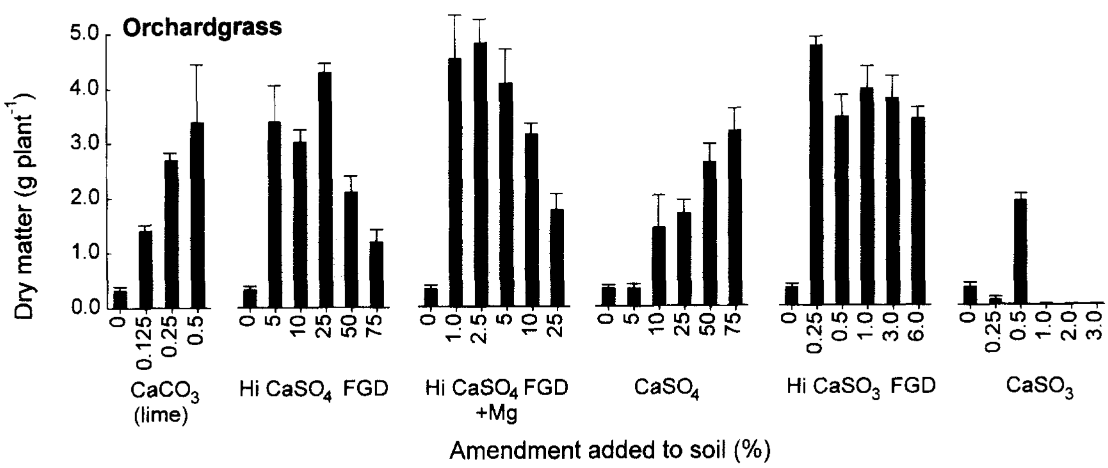

Figure 1 Whole-plant dry matter of orchardgrass grown on acid soil amended with different levels of three FGD-BPs and chemical-grade $CaCO_3$, $CaSO_4$ and $CaSO_3$. The T above each bar is the standard error of the mean

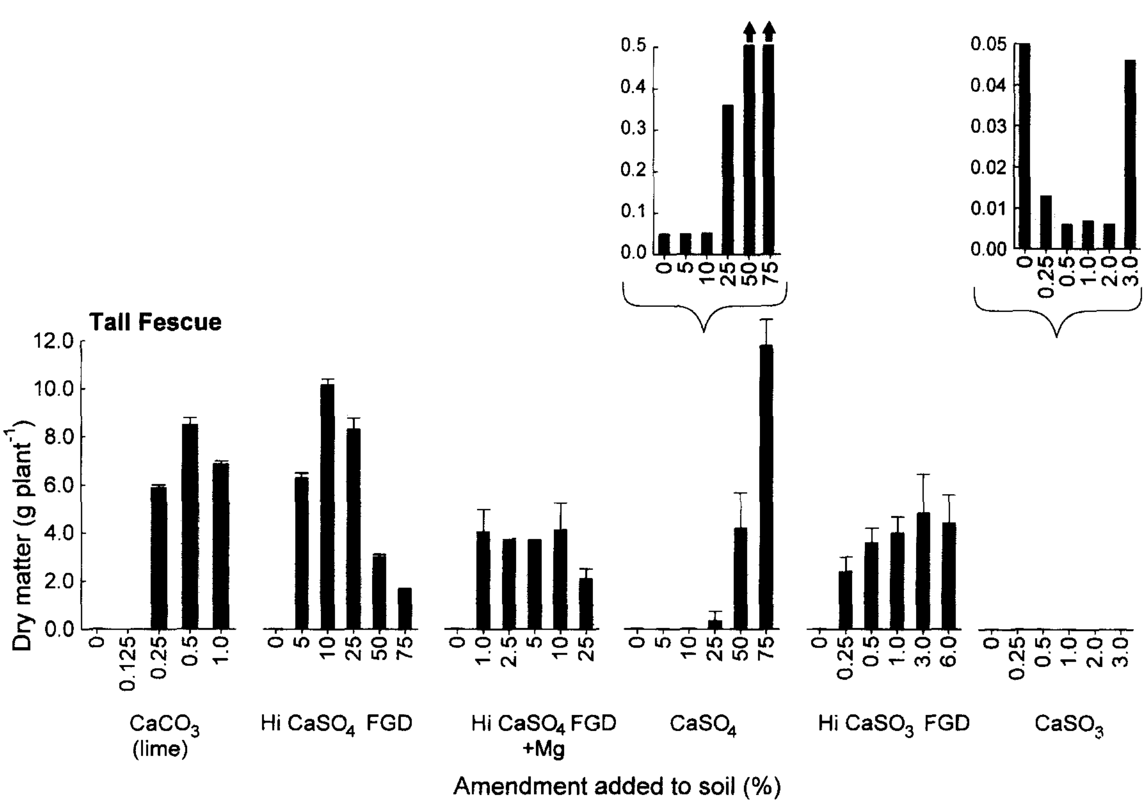

Figure 2 Whole-plant dry matter of tall fescue grass grown on acid soil amended with different levels of three FGD-BPs and chemical-grade $CaCO_3$, $CaSO_4$ and $CaSO_3$. The T above each bar is the standard error of the mean

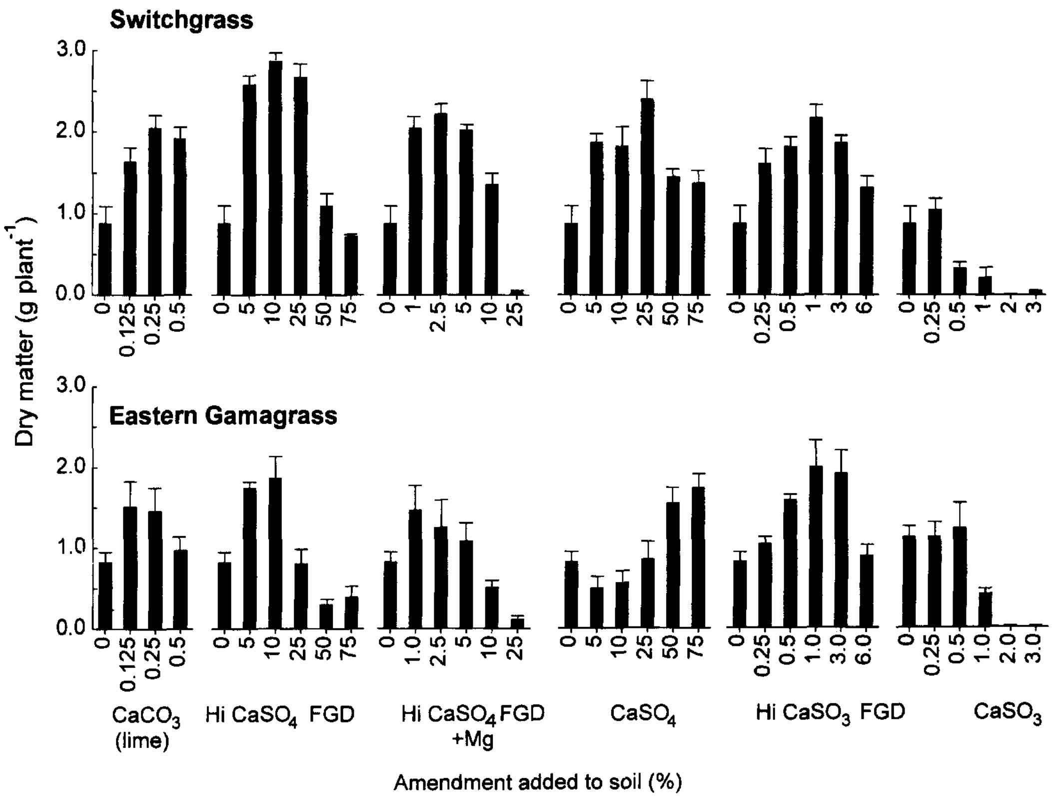

Figure 3 Whole-plant dry matter of switchgrass (upper) and eastern gamagrass (lower) grown on acid soil amended with different levels of three FGD-BPs and chemical-grade $CaCO_3$, $CaSO_4$ and $CaSO_3$. The T above each bar is the standard error of the mean

from addition of Mg to this FGD-BP, grasses appeared to receive greater benefit at lower levels than legumes. Maize also benefited from added Mg, with 1–2.5% in soil mixes providing highest growth[6].

Except for switchgrass, the species grown with chemical-grade $CaSO_4$ did not have the highest growth until the highest level (75% in soil mixes) was added (*Figures 1–4*). In contrast, the high-$CaSO_4$ FGD-BP provided the highest growth at lower levels than did chemical-grade $CaSO_4$. This probably occurred because the high-$CaSO_4$ FGD-BP contained nutrients beneficial to plants (*Table 1*) in contrast to chemical-grade $CaSO_4$. High-$CaSO_4$ FGD-BPs might also have contained toxic elements, because DM decreased at the highest levels. Similar results were noted for maize[6,7]. It was interesting that chemical-grade $CaSO_4$ was not detrimental to growth of these plants at the high levels used (75% in soil mixes), which might indicate that $CaSO_4$ *per se* was not detrimental to plant growth. In addition, the reduced or no increase in DM over controls with $CaSO_4$ at low levels (5–10%) might indicate that the soluble Ca displaced Al^{3+} (or other monomeric Al species) from exchange sites, and this Al in soil solution may have become toxic. Other research showed that relatively high amounts of Al were obtained in initial leachates from columns when this same acid soil was surface-amended with high-$CaSO_4$ FGD-BP[10]. Root elongation was reduced when $CaCl_2$ and $CaSO_4$ were added to acid soil, and $CaCl_2$ had greater effects than $CaSO_4$[11]. The higher levels of $CaSO_4$ were beneficial to plants, which indicated that high sulfate could have inactivated toxic Al[4].

Each of the plant species studied received some benefit from addition of the high-$CaSO_3$ FGD-BP at the lower levels used in this study; grasses received more benefit than legumes (*Figures 1–4*). White clover benefited more at lower treatment levels than alfalfa. At the highest level used (3% in soil mixes), DM of switchgrass and eastern gamagrass declined. Maize studies indicated that levels of high-$CaSO_3$ FGD-BPs > 3–5% were detrimental to growth[6,7]. This was the reason for not using higher levels in the current study. This particular high-$CaSO_3$ FGD-BP appeared to have lower sulfite and higher calcium carbonate equivalence (liming ability) (*Table 1*) than those used in other studies[6,7], and was not as detrimental to plant growth as some other high-$CaSO_3$ FGD-BPs. Although precautions were taken to prevent oxidation of sulfite to sulfate (BP was kept frozen until used), some oxidation may have occurred in this BP by the time plants were harvested. The FGD-BP may also have arrived from the power plant with less $CaSO_3$ than other high-$CaSO_3$ FGD-BPs studied[6]. Sulfite in CCBs oxidizes to sulfate relatively rapidly[12].

Switchgrass and eastern gamagrass appeared to be somewhat more tolerant to chemical-grade $CaSO_3$ at the low levels used than orchardgrass, tall rescue, alfalfa and white clover (*Figures 1–4*). These results indicated that sulfite can be detrimental to growth of these plant species at low levels, and similar results were noted for maize[6,7].

CONCLUSIONS

The forage plant species used in the current study differed in ability to grow on acid soil amended with different levels of FGD-BPs. The FGD-BPs were beneficial to plant growth if applied to acid soil at appropriate levels. The warm-season grasses (switchgrass and eastern gamagrass) were more adversely affected by the high-$CaSO_4$ FGD-BPs at high levels than the cool-season grasses (orchardgrass and tall fescue) and legumes. The grasses responded more positively to Mg added to the high-$CaSO_4$ FGD-BP at lower levels

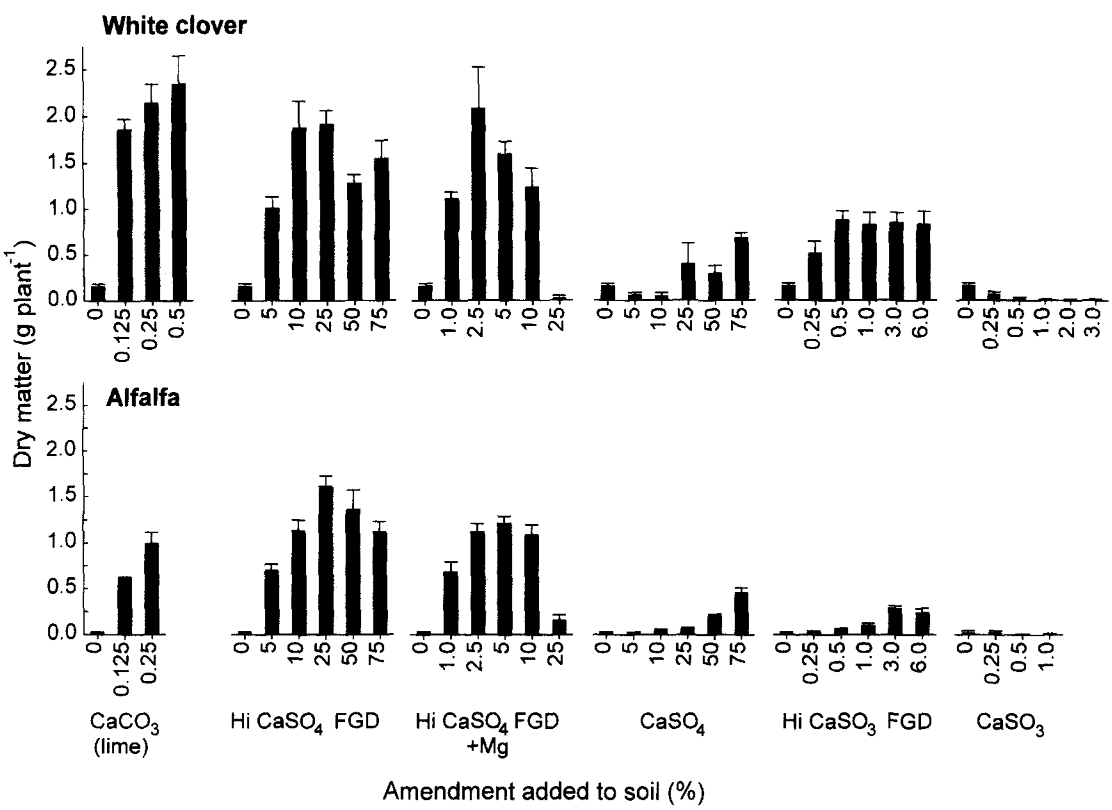

Figure 4 Whole-plant dry matter of white clover (upper) and alfalfa (lower) grown on acid soil amended with different levels of three FGD-BPs and chemical-grade $CaCO_3$, $CaSO_4$ and $CaSO_3$. The T above each bar is the standard error of the mean

than the legumes. The plants could be grown at very high levels of $CaSO_4$, but sulfite added to the soil as chemical-grade $CaSO_3$ did not benefit plant growth.

ACKNOWLEDGEMENTS

Preparation of the Figures by Ms S. S. Boyer is greatly appreciated.

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